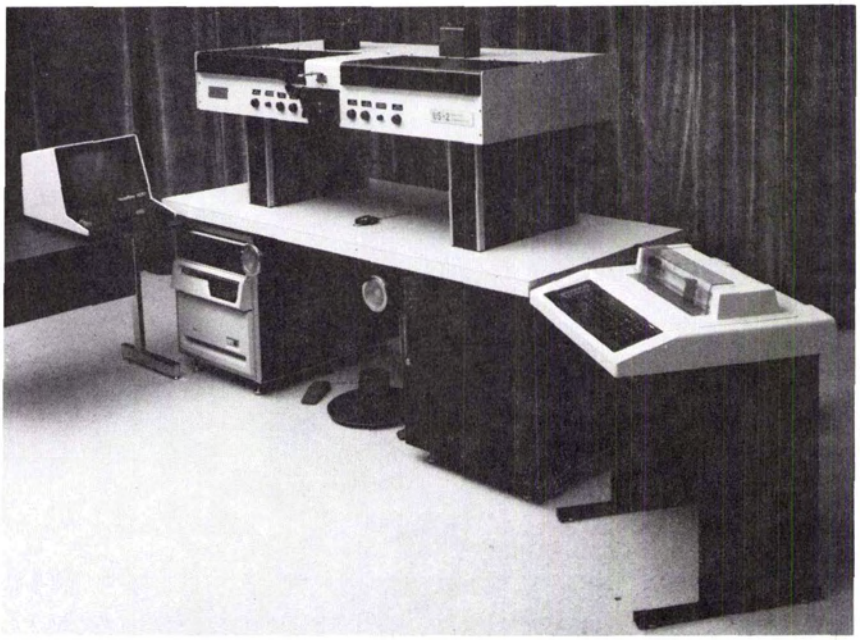

FRONTISPIECE. The US-2 Analytical Stereoplotter.

RICHARD H. SEYMOUR
Helava Associates, Incorporated
Southfield, MI 48034

US-2 Analytical Stereoplotter

The US-2 is truly a practical stereoplotting system offering good human engineering and high operational performance at an affordable price.

(Abstract on next page)

INTRODUCTION

THE US-2 ANALYTICAL STEREOPLOTTER was designed specifically for the commercial market, with a primary design goal of producing an instrument with an attractive cost/performance ratio. The resulting system has several characteristic design features. For one, the optical-mechanical portion of the system is placed at the eye level of the operator, resulting in a very simple optical path. For another, the mechanisms are designed to be stable, rather than absolutely accurate, with computer corrections applied to achieve the desired accuracy. This drastically reduces the cost of mechanical parts. Also, the servo drives are based on a proprietary pinch-roller principle which decouples the drives from the guiding mechanisms. This serves to improve instrument stability and decrease its cost.

As important as these optical-mechanical design features are, even more important innovations are incorporated into the control architecture of the US-2. This architecture, which is based on the principle of distributed processing, separates the real-time control function from the application function. All real-time digital functions are performed by the DIGIPRO (DIGItal PROjector) microprocessor-based interface. This offers two advantages: (1) It relieves the host computer of any time-critical tasks, giving greater flexibility in

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host selection; and (2) it guards against obsolescence. Since the real-time photogrammetric tasks performed by DIGIPRO are basic tasks which won't change, advances in computer technology will not cause the US-2 to become obsolete. DIGIPRO will be able to readily accept a new host.

The US-2 applications software package is a comprehensive package which has been proven in practice. It is organized in modular form and written in FORTRAN to simplify expansion or modification of the programs by the customer for his special applications. These programs are run under the RSX-11M operating system which is a real-time multi-tasking system. This allows the computer to be used to control the US-2 and perform other computational tasks concurrently. This could also allow the computer to control two stereoviewers at the same time, thereby reducing the cost of additional US-2 systems.

Photogrammetry is entering an era where increased emphasis is being placed on digital techniques. The US-2 fits nicely into this mode as well as serving as an excellent transitional tool from analog to digital. Since it is both adaptable and flexible, it can support and increase the efficiency of an entire photogrammetric organization, providing for eventual integration of all photogrammetric instruments into an operational system.

ABSTRACT: *The US-2 Analytical Stereoplotter, manufactured and marketed by Helava Associates, Incorporated (HAI), is an instrument designed especially for the commercial marketplace, offering excellent performance at an attractive price. The design of the US-2 includes several innovative features in its optical-mechanical solution, servo drive assembly, and control system.*

The US-2 is intended for aerial triangulation, large and small scale mapping, profiling, cross-sectioning, and digital data collection. Operator control is exercised through the CRT terminal, which allows access to all data items of interest to the operator and provides prompting by the programs for various operating procedures. Movement through the model is controlled by two handwheels, a footwheel, a free-hand cursor, and an optional tabletop Z control.

US-2 operation is controlled through a comprehensive set of software. This software runs under a real-time multi-tasking operating system which permits execution of other programs simultaneously with the stereoplotting programs, or the control of two US-2's by one computer.

A typical US-2 Analytical Stereoplotter configuration consists of a stereoviewer, control interface, host computer with associtated peripherals, plotting table, and computer programs. A brief description of these major components is given below. Operator controls include a CRT terminal for communication with the host computer; handwheels, footwheel, and freehand control for model motion; optics controls for illumination, rotation, and base-in/base-out viewing; and various function and status switches.

Hardware

STEREOVIEWER

The stereoviewer consists of two precision *X-Y* photo stages, a binocular optical viewing system, stage illuminators, and the major operator controls. It is designed to optimize system performance by providing high dynamic response and mechanical stability. In addition, it has a design approach condusive to excellent optical performance. It is suitable for use with either color or black-and-white photography and accommodates film positives or glass plates up to 25 cm (10 in.) square. An optional configuration, able to accommodate input materials up to 25 cm by 50 cm (10 in. by 20 in.), is also available.

The *X-Y* stages provide precise positioning of the input photographs with respect to stationary optical viewing axes. The measuring mechanisms, which provide smooth, silent operation, employ a design which separates the guidance function from the drive function, thereby reducing potential error sources. The drive actuator consists of a proprietary pinch-roller servo drive. One extremely nice feature of this design is that, if a mechanical limit is encountered, the pinch-roller will simply slip on the actuator, resulting in no mechanical damage or physical loss of position.

The measuring and servo feedback element of the stages consists of precise linear encoders with a least count of 0.001 mm. The measuring system has a precision of 0.001 mm with a maximum slewing speed of 40 mm per second. Stage accuracy is typically 0.0025 mm RMS per axis after computer-applied stage corrections to remove systematic error.

The US-2 optical system provides a high-resolution image with a field of view of 24 mm diameter at a fixed magnification of 8× using 10×

eyepieces. Other magnifications can be provided, such as 12× or 16×, by replacing the eyepieces. In addition, the optical system has been designed to accept an optional 4:1 zoom system, providing a continuous magnification range from 6× to 24×. With the optional zoom system, the field of view is 190 mm divided by magnification, i.e., over 31 mm at 6× and 8 mm at 24×.

Each optical path is viewed through a rhomboid eyepiece assembly which provides independent focus, adjustable interpupillary distance from 50 mm to 80 mm, and squint adjustment for both axes. The large eye relief of the optical system permits the operator to wear eye glasses. In addition, independent 360° image rotation is provided for each path and an optical switch is provided to interchange the images in the viewing eyepieces (base-in/base-out). As an option, the stereoviewer can be provided with a second set of eyepieces, located at the back of the viewer, to allow two operators to view the stereomodel at the same time. Another option available is binocular viewing of each stage.

Opaque measuring marks are provided with the system. Luminous marks are available as an option, and are required if the zoom option is chosen. The measuring marks are inserted into the optical path directly below the stereo photographs and are solidly tied to the measuring system with no moving optical elements between the marks and the photographs. This provides a stable reference for accurate stereo measurements.

The operator controls the system through the handwheels and footwheel. These controls are designed for smooth response and sensitivity, with both their sensitivity and direction controlled by the software. Thus, it is a simple matter to alter the *X*,*Y*, and Z control of the handwheel and footwheel by a simple reassignment. In addition to the handwheels, *X*-*Y* motion can be controlled through the freehand cursor control located on the tabletop directly in front of the operator. This control, which consists of a digitizer tablet imbedded in the table top and a cursor, is designed to provide slewing, *X*-*Y* plotting, and precise pointing capabilities to supplement the handwheels. An optional Z control, which can be located on the tabletop, can be incorporated to provide hand control in place of, or in addition to, the footwheel and footswitches.

CONTROL INTERFACE

The control interface of the US-2 is based on the proprietary DIGIPRO concept, which integrates all real-time logic and software functions into one compact unit. This unit incorporates a multiple microprocessor design to not only handle the servo interface and operator command inputs, but also to perform the projective transformations in real time. The DIGIPRO is capable of stand-alone operation, although at slightly reduced accuracy levels, because the math model in DIGIPRO is an ideal math model. To provide accuracy commensurate with the remainder of the US-2 system, minor corrections are supplied three to four times per second from the host, which has a complete math model including all the photogrammetric corrections such as lens distortion, Earth curvature, and atmospheric refraction.

It should be noted that, without the DIGIPRO, the host computer would have to perform all real-time functions and provide updates to the servos 30 or more times per second. Thus, this concept greatly reduces the real-time computational load of the host computer. This releases the computer capacity for other concurrent computations or allows the operation of multiple units from a single host computer.

The DIGIPRO communicates with the host computer over a standard serial data communication channel; that is, the DIGIPRO looks like a standard terminal to the host. The data exchange between the host and the DIGIPRO includes such things as the output of coordinate data from the DIGIPRO to the host computer or the input of model setup parameters from the host to the DIGIPRO. Since the data channel is a standard serial communications channel, DIGIPRO can readily communicate with essentially any computer.

The DIGIPRO is an open-ended design which can be expanded to meet user requirements. It is implemented using standard modules and is completely self-contained. It is packaged in one of the pedestals of the table upon which the viewer is placed.

CONTROL COMPUTER

The flexibility of the US-2 design makes it possible to use almost any control (host) computer. This added flexibility is mainly due to three reasons: (1) the applications software is nearly all FORTRAN; (2) the real-time computational load of the host computer has been greatly reduced; and (3) the control interface communicates with the host over standard serial data communication channels. This allows the use of a computer as simple as a PDP-11/23 with local floppy disks or as elaborate as a PDP-11/44 with dual cartridge disks as the host computer. Use of a minicomputer other than the DEC PDP-11 series can be accommodated with some software modifications to compensate for differences in operating systems.

The standard host computer for the US-2 is the PDP-11/34, a general-purpose digital computer manufactured by Digital Equipment Corporation. It is equipped with 64K words of memory, 10.4 million bytes of interchangeable cartridge disk memory, a CRT terminal, and a teleprinter.

The CRT terminal is used to provide basic operator communications and control with the US-2. It is used to enter and display data as well as enter operator commands to the applications software. It provides a display size of 24 lines of 80 characters each. The US-2 utilizes the upper portion of the screen to provide a real-time display of operator-selected data items, such as ground, model, or photo coordinates.

In addition to the standard peripherals mentioned above, the computer can be easily configured with a wide variety of peripherals to meet the particular needs of the user. These can include additional memory, additional disk units, magnetic tape units, floppy disks, cassette tape units, and so on. All of these devices are standard peripherals which can be either incorporated in the initial system or added later.

PLOTTING TABLE

The flexibility of the US-2 software permits virtually any "smart" plotting table to be incorporated into the system, that is, one that provides its own plotter control. The user can select a small desktop plotter for proof plotting, a large plotting table for normal manuscript generation, or no plotting table at all, depending on his needs and the intended use of the US-2. For example, if the user has access to an off-line plotting table, he can collect his manuscript data digitally and then plot these data on the off-line plotting table at his convenience. Or, if the US-2 is to be used for triangulation data collection only, no plotting table is required.

The characteristics of the plotting tables normally used to generate manuscripts is readily available from the various manufacturers, and no attempt is made here to present these data. For any table used, the US-2 software would output the commands necessary to control the plotting table on-line with the stereoplotter. However, the plotting table is interfaced to the computer in such a way that it is possible to also operate the table off-line, simultaneously with the US-2, as a separate unit.

Software

The US-2 is provided with a complete set of both system and applications software. The system software provides the necessary support to develop, build, and execute the applications software. The applications software is intended to provide the highest computational accuracy of any stereoplotter in the world while at the same time to provide the flexibility to meet the individual user's requirements.

SYSTEM SOFTWARE

The operating system currently used with the US-2 is the DEC RSX-11M Operating System, a multi-tasking system. RSX-11M provides (1) on-line support of program and overlay loading into memory from the disk, (2) use of standard peripherals, and (3) the processors necessary to support software development in FORTRAN and assembly languages.

RSX-11M can provide multi-tasking capability, which greatly enhances the host computer's use as a general purpose computing facility. Because much of the real-time computational load has been taken over by the DIGIPRO, it is now feasible to run one or more additional tasks simultaneously with control of the US-2. For example, while one operator is plotting contours at the stereoplotter, a second operator can be running a different program, such as strip adjustment, or doing software development from a second terminal. This feature could also be used to allow the host computer to control more than one stereoviewer at the same time, thereby reducing the cost for a second US-2 system.

PROGRAM STRUCTURE

US-2 operation is under control of a composite program which is composed of sets of program modes. These program modes, which are organized in modular form made up largely of separate subroutines, are run as an overlay system under the RSX-11M operating system. They are organized in such a way that no operator action is required to enter a program mode other than to request that mode. This organization offers comprehensive operations in a structure which allows it to be custom-tailored to specific operations. The potential of the US-2 in this regard is exceptionally high since the DIGIPRO is performing the critical real-time computations. Therefore, the timing of additional programs run on the host does not adversely effect stereoplotting operations.

Maximum use is made of FORTRAN, with those programs not written in FORTRAN made FORTRAN-callable. This again allows for simple modification of, or addition to, the software package for special applications. This flexibility and ease of custom-tailoring the software for special applications greatly increases the value of the US-2.

The current US-2 application programs provide capabilities in four main areas:

- Traditional stereoplotter operations,
- Strip Triangulation,
- Data manipulation functions, and
- Off-Line Programs.

This software is able to accommodate virtually unlimited ranges on focal length and other photogrammetric parameters with no decrease in computational precision. Provision is made to correct for atmospheric refraction, Earth curvature, lens distortion (radial and asymmetrical), film deformation, and principal point offset. In addition, the programs enable the operator to input and display

coordinate values directly in any grid-system ground coordinates, as well as stereomodel coordinates.

STEREOPLOTTING PROGRAM MODES

Standard stereoplotting programs delivered with the system consist of a set of individual program modes which perform the various functions required for the operation of the system. These programs are combined in a software system which provides smooth transition between system operations, requiring a minimum of operator intervention.

Interior Orientation. This mode is used to establish a precise photo-to-stage coordinate transformation, based on the measurement of up to nine fiducial marks. It provides for operator-selection of the type of transformation from a simple intersection (to define photo center and rotation on the stage) up through a second-order polynomial fit, depending on the amount of data available for the fiducials. The program assists the operator in the location of the fiducial marks, automatically slewing to their approximate location, and automatic and convenient engagement and disengagement of stage motions to permit fast and accurate pointing. The computational phase is entered into automatically once all the indicated fiducials have been measured.

Visit Points. This mode is used to allow the operator to observe and record coordinates for parallax points, pass points, and ground control points for use in the relative/absolute orientation computation. It provides for automatic slewing to specified points. It also allows the operator to move both photos simultaneously, or to hold one photo fixed and move the other photo relative to it for fast and convenient removal of parallaxes and recording of the resulting photo coordinates.

Exterior Orientation. This mode performs an automatic relative or combined relative/absolute (exterior) orientation based on the orientation data points gathered in the Visit Points mode. In this mode, the operator is able to select the orientation elements for which a solution is to be computed based on the setting of data items. Thus, the operator can choose to perform a relative orientation or an exterior orientation, or something in between, depending on the data he has available for the model. The program allows for the intermixing of parallax points, pass points, and ground control points in the solution. In addition, operator-selectable weights are used to influence the relative effects of the orientation elements and data values used in the solution. The solution is basically a two-photo rigorous block adjustment by bundles. The quality of the solution is periodically displayed to the operator in the form of individual photo and ground residuals of every point and the standard deviation of all the photo residuals. This can assist in locating bad points in the solution. The program also computes best-fitting ground coordinates for non-control points to assist in the automatic revisiting of orientation points by the Visit Points mode.

Table Preparation. If a plotting table is included in the system, this mode is used to set up the plotting table coordinate system for the selected plotting operation; either to the stereomodel ground coordinate system for *XY* plotting or to the direction and spacing of profiles for profile plotting. This allows the operator to establish the relationship between the stereomodel and the manuscript for plotting. Using this mode, it is possible to put a previous manuscript on the plotting table and modify or update the plotted information without cumbursome manual intervention by the operator. All that is required is that the operator identify and measure several points on the manuscript.

XY Plotting. This mode is used to plot planimetry, contours, or discrete points, operating directly in ground coordinates if desired. It allows the operator to move about the stereomodel in the active ground (or model) coordinate system, and generate ground information either graphically (if a plotting table is available on-line) or digitally. It also provides the operator with the ability to connect discrete points with straight-line plots, which can be particularly useful in plotting man-made features, grids, buildings, and so on.

Profiling. This mode is used to generate terrain profiles, that is, collect elevation information along a particular azimuth through the model. It provides the operator with the ability to select the direction in which profiles will be generated and the spacing between profiles. Means are provided within the program to assist the operator in determining the direction through the model (azimuth) along which elevation information is to be collected. The program, which can be used to efficiently collect a digital terrain model (DTM), can record data digitally or graphically.

Point Measurement. This mode is used to collect a series of discrete points from a stereomodel. It is designed to allow the operator to locate and measure a series of points and save their corresponding coordinates in a disk file. Each point is stored with an ID, which can be either a default ID generated by the computer or an operator-selected ID which will override the computer-generated ID. The program allows for multiple measurements of a point with the mean and the variance of the multiple readings displayed on the CRT. When recorded, the mean value of the coordinates will be recorded. This mode allows the operator to delete or remeasure individual points, based on the point ID.

STRIP TRIANGULATION PROGRAMS

The applications software package also includes a complete strip triangulation capability, from data

collection through adjustment and stereoplotter set-up. These programs form a stand-alone package performing all the necessary functions and data manipulation for strip triangulation. They can also be used to collect (and preprocess) data for off-line block adjustment programs.

Data Collection. The strip triangulation data collection function is performed by the Bridging mode. This mode is used to analytically orient successive photographs along a strip, with automatic analytical scale and coordinate transfer between each successive model. The system has base-in/base-out viewing to accommodate this data collection operation. The programs assist the operator as much as possible with the required operations to increase the speed of the data collection function. The programs return automatically to old scale transfer points exactly as measured, thereby eliminating the need to physically mark these points prior to measurement. Furthermore, all data manipulation and handling are performed automatically with no operator intervention. The operator has complete freedom in the number and types of points he wishes to measure along the strip. In addition, the programs are designed to allow the operator to stop work at any point and resume at a later time without loss of data and with a minimum of effort.

Adjustment. The strip triangulation package includes a set of programs which will perform a polynomial adjustment on the collected strip data so as to orient the entire strip to the ground. The programs utilize the data collected directly with no operator intervention or data manipulation required other than to specify the ground control. The programs provide the capability to perform up to a third-order elevation adjustment independently along and across the strip and a second-order conformal horizontal adjustment with operator-selectable terms. The data collected include both photo and strip coordinates for each point, so the data can be used for other off-line adjustment programs if so desired with a minimal amount of data manipulation.

Model Set-Up. The final program in the strip triangulation package is the Model Set-Up program. This program uses the data collected in the Bridging mode and the results of the strip adjustment to calculate shutdown data for each model in the strip, that is, the data necessary to establish an absolutely-oriented model on the US-2. Thus, any model from the strip can be reset on the US-2 without requiring the operator to perform a relative/absolute orientation.

DATA MANIPULATION FUNCTIONS

In addition to the various program modes discussed above, the US-2 applications software has a set of functions which are available within the normal mode of operation to perform various data manipulation functions. These functions are designed such that they return to the normal mode of operation upon their completion. They can be used to examine and modify data items, continuously display selected data items on the CRT, assign the data item to be effected by the incremental input controls, establish the origin for direct-distance computations, and determine a reference azimuth through the model. All the data items in the system—orientation elements, control points, ground coordinates, photo coordinates, etc.—are contained in memory and are easily accessible by the operator through the use of these functions. One additional function is a special "Print" function which will copy the contents of the CRT screen to the DECwriter. This can be used to obtain a hard copy of intermediate results, such as orientation residuals, for a permanent record.

OFF-LINE PROGRAMS

In addition to the composite programs described above, which control the normal stereoplotter operations, several supporting programs are included with the standard software package. These programs are stand-alone programs written in FORTRAN, and are intended for use in pre- or post-processing US-2 data or input parameters. These programs are described below.

Model Parameter Input. This program is used to set up a model parameter file for a particular stereomodel. It is designed to allow the operator to input the particular parameters for his stereomodel in a convenient off-line operation. Thus, such information as calibrated coordinates of fiducials, approximate camera parameters, ground control points, and so on, can be set up in a parameter file before the operator starts work on the US-2.

Stage Calibration. This program is designed to provide the operator with a fast and convenient method of checking the current calibration data associated with each stage and changing this data if necessary. This program is designed to work with a calibrated grid plate which the operator measures. The program assists in this operation by automatically positioning the stage at the approximate location of each grid intersection. Multiple readings are allowed, with the standard deviation of the multiple readings displayed to the operator. When recalibrating a stage, the calibration data are stored in a disk file which is downloaded to the control interface upon US-2 initialization.

Lens Distortion Computation. This program (RADLEN) accepts a table of lens distortion amounts at various radii from the point of intersection of the lens axis and the film plane and calculates the radial lens distortion coefficients for the US-2 application programs. For the US-2, these

lens distortion coefficients are the coefficients of an odd-order polynomial.

Playback. This program provides a means of generating graphic output from digital data recorded in the *XY* Plotting or Profiling modes. This program takes the stored digital data from either of these modes and outputs them to the plotting table in an off-line operation. It also provides the operator with the opportunity to perform a table preparation prior to output, to replace any table orientation data stored with the digital data.

Diagnostics. These programs provide a convenient method for the operator to check and verify the proper operation of the hardware or, in the case of a malfunction, to determine the source of the malfunction.

Applications

The US-2 Analytical Stereoplotter can certainly be used to perform any traditional stereoplotting operation. However, its flexibility and versatility are just beginning to be exploited. Because the US-2 by its very nature is inherently digital, and because it is controlled by a general-purpose computer, the capabilities and potential uses of the US-2 are almost unlimited. It can certainly improve the performance and the cost-effectiveness of a photogrammetric organization, both in standard and non-standard photogrammetric applications.

In the triangulation area, the US-2 can be used either as a stereocomparator or as a stereoplotter. The ability of the system to preposition the stages to known points provides two benefits: (1) It is not necessary to pre-mark scale transfer points, and (2) the operator is greatly assisted in locating and measuring points. With the computer controlling the operation, some on-line editing of points is achieved, greatly reducing the need to re-establish a model to remeasure a point. In addition, the adjustment can be performed on the same computer which is controlling the US-2. The data collection scheme used is flexible enough to also allow the standard US-2 programs to be used to collect data for other off-line adjustment routines with a minimal amount of data manipulation.

In the stereoplotting area, where digital data collection is becoming increasingly important, the US-2 provides digital information as a primary output of the system, not a by-product. The US-2 provides the highest accuracy, thereby allowing photography to be flown higher to achieve the same accuracy as is obtainable from most analog instruments. Also, it is possible to use non-standard photography or photography from dissimilar cameras since the camera parameters are mathematical (with virtually unlimited range) and are independent for each photograph.

For any operation which requires multiple resets of the same model, such as for map revision, collection of different types of information, and so on, the US-2 can prove to be very cost-effective. The US-2 can reset a model from stored digital data in only a few minutes. This reset model will be identical to the stored model except for the interior orientation which determines the relationship of the photo to the stage.

For close-range applications, the US-2 is ideally suited because of its mathematical solution to the projective geometry. There are no inherent limits to the range of coordinates or camera parameters. The stereomodel is established mathematically and can be formed from non-standard photography. Most close-range applications require high accuracy measurements and digital output, both of which the US-2 provides. The US-2 can be readily programmed to perform special functions, depending on the close-range application.

While the applications discussed above by no means represent the full capability of the US-2, they do represent areas where standard software packages have been developed. However, it is important to keep in mind that the US-2 software has been designed and developed to be extremely flexible and easy to modify. Thus, the user is able to add or modify software to tailor the system to his particular needs. The potential applications are seemingly unlimited.

Conclusion

The US-2 Analytical Stereoplotter is a system which incorporates several cost-reducing innovations which represent significant advances in the field of analytical plotters. The US-2 is designed to give the highest stereoplotting accuracy of any present production stereoplotter while at the same time providing the utmost flexibility.

The software available for the US-2 not only exploits the system's maximum accuracy, precision, and speed to provide comprehensive operations needed for mapping applications and strip triangulation capabilities; it also offers these operations in a software structure which is well-suited for user modification to allow the US-2 to be custom tailored to a particular application. The US-2 is truly a practical stereoplotting system offering good human engineering and high operational performance at an affordable price.

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